Reliability analysis of RC slabs with or without FRP strengthening to blast loads

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ABSTRACT

With a rise in blast attacks on structures in recent years there is a desire to increase the blast resistance of many types of existing structures. Studies of using fibre reinforced polymer (FRP) composites to strengthen RC structures to resist blast loads have been reported. The general conclusions are that the blast loading resistance capacities of RC structures strengthened with FRP are enhanced. Previous studies also developed empirical relations to construct P-I curves of RC slabs without or with FRP strengthening. This study performs reliability analysis, taking into account the randomly varying blast loads and structural parameters, to calculate probabilities of failure of reinforced concrete slabs and observe the effectiveness of the FRP strengthening. P-I curves with a damage criterion based on support rotation are used to generate the limit state function for reliability analysis. Variations of the blast loadings and structure parameters are taken as normally distributed with mean and variances acquired from literature. From the numerical results, the effectiveness of the FRP strengthening on RC slabs is examined.

KEYWORDS

Reliability analysis; blast loading; random variation; FRP strengthening; RC slab.

INTRODUCTION

Since September 11 2001, terrorism has become an increasingly prominent threat to society. Many studies have been carried out for effective design of new and strengthening of existing structures for economy and personnel protections against blast loadings. Fibre reinforced polymer (FRP) is a composite material usually comprising of a resin strengthened with glass, carbon or aramid fibres. This can be applied to concrete beams, columns and slabs in strips or sheets bonded with an epoxy. FRP is increasingly being used in structural engineering applications. Its high strength and stiffness to weight ratios, together with high durability and resistance to corrosion and heat make it particularly useful in blast resistant design. Crawford et al. (1996) conducted an analysis on the effectiveness of FRP wrap retrofitting on the blast load resistance of reinforced concrete columns. Results showed that FRP wraps were an effective way of improving columns resistance. Buchan and Chen (2007) presented an extensive review of the experimental and finite element model available for retrofitting structures with FRP and polymers against blast loading. It was found that FRP strengthening is in general effective in enhancing blast loading resistance capacity. However, it was also identified that the variable nature of the retrofitted structures, materials and techniques makes it difficult to draw comparisons between studies into FPR strengthening. Mutalib and Hao (2011a, b) conducted impact tests on FRP strengthened RC beams and slabs, and performed numerical simulations to derive empirical relations for constructing P-I diagrams of RC structures without and with FRP strengthening.

Significant variations in the effectiveness of FRP strengthening have been reported. Atadero and Karbhari (2008) identified the major sources of variability in FRP material strength and bonding
strength. They proposed reliability based design for FRP strengthening of concrete structures. The mean value of composite properties was used as the design value and resistance factors for use in design codes were determined based on the coefficient of variation of the FRP strength. Wang et al. (2010) explored the feasibility of creating reliability based guidelines for externally bonded FRP composites. Fibre properties, fibre orientation, and the care in workmanship were all found to be significant factors in the characteristics of the FRP.

Besides variability in FRP material property, random fluctuations in blast loading and RC structures are also inevitable. Low and Hao (2002) used reliability analysis to model the flexural and direct shear responses of one-way reinforced concrete slabs subjected to explosive loading. As in Low and Hao (2001), blast loading was presumed to be uniformly distributed with the mean values and standard deviations at different scaled distances estimated from 7 prediction approaches including empirical relations and design charts. Borenstein and Benaroya (2009) conducted a probabilistic sensitivity analysis of a clamped aluminium plate subjected to randomly varying blast loadings. ConWep, which provided the best results in Bogosian et al. (2002), was used to generate the mean peak pressure and duration with uniform distribution assumptions. Netherton and Stewart (2010) performed a statistical analysis of explosive loading test data and assessed the sources of variability to develop a probabilistic model. Hao et al. (2010) performed reliability analyses to determine the failure probabilities of RC columns due to blast loads. P-I curves developed by Shi et al. (2008) were utilised to develop the limit state function for analysis. Uncertainty in RC column dimensions and material properties, as well as the random variations of blast loading estimations were considered in the analysis.

In this paper, the procedure developed in Hao et al. (2010) is used to calculate the failure probabilities of RC slabs without and with FRP strengthening. P-I diagrams developed by Mutalib and Hao (2011b) are used to model RC slab failure and derive the limit state function. The random variations in blast loading predictions, RC slab material and dimension properties, and FRP material properties are considered. The effectiveness of FRP strengthening of RC slabs is demonstrated.

**P-I CURVES FOR RC SLAB DAMAGE ASSESSMENT**

Mutalib and Hao (2011b) conducted intensive numerical simulations to construct P-I diagrams of RC slabs of different conditions without and with FRP strengthening. Three levels of damage were defined according to the support rotations (UFC 2008). As shown in Figure 1, when support rotation is 2 degrees, yielding of the reinforcement is first initiated, and the damage of the wall is termed as low (LD). When the support rotation is 4 degrees, the element loses its structural integrity, and moderate damage (MD) occurs. At 12 degrees support rotation, tension failure of the reinforcement occurs and the damage is classed as severe (SD). Figure 1 also shows the typical damage modes of one-way and two-way slabs corresponding to the different pressure and impulse (Mutalib and Hao 2011).

Based on the intensive numerical data, the P-I diagrams can be expressed as

\[
(P - P_o)(I - I_o) = A \left( \frac{P_o + I_o}{2} \right)^\beta
\]

in which \(P_o\) and \(I_o\) are the pressure and impulse asymptotes of the P-I curve, \(A\) and \(\beta\) are constants, which depend on the RC panel configuration and degree of damage. Based on intensive numerical simulations, empirical relations were derived to calculate \(P_o\), \(I_o\), \(A\) and \(\beta\). They depend on panel depth \(d\), panel height \(H\), panel width \(b\), unconfined concrete compressive strength \(f_{cu}\), reinforcement ratio \(\rho\), epoxy strength \(f_e\), FRP strength \(f_{frp}\), and FRP thickness \(t_{frp}\). Owing to the page limit, the empirical relations are not given here. Interested readers are referred to (Mutalib and Hao 2011b).
In this study, 6 panels, three without FRP strengthening but increasing reinforcement ratio (S1-S3), and three with FRP strengthening and increasing FRP thickness (F1-F3) are considered. The concrete density of 2400kg/m$^3$, Poisson’s ratio 0.3; and reinforcement steel density 7800kg/m$^3$, Young’s modulus 200 GPa, Poisson’s ratio 0.3, and yield stress 415 MPa are assumed to be deterministic. Other parameters are considered as random. They respective mean values are given in Table 1.

<table>
<thead>
<tr>
<th>Slab</th>
<th>$\rho$ (%)</th>
<th>$f_{cu}$ (MPa)</th>
<th>$d$ (mm)</th>
<th>$H$ (mm)</th>
<th>$b$ (mm)</th>
<th>$f_{frp}$ (MPa)</th>
<th>$t_{frp}$ (mm)</th>
<th>$f_e$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.87</td>
<td>30</td>
<td>200</td>
<td>2700</td>
<td>2500</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S2</td>
<td>1.4</td>
<td>30</td>
<td>200</td>
<td>2700</td>
<td>2500</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S3</td>
<td>4.0</td>
<td>30</td>
<td>200</td>
<td>2700</td>
<td>2500</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>F1</td>
<td>0.87</td>
<td>30</td>
<td>200</td>
<td>2700</td>
<td>2500</td>
<td>2085</td>
<td>1</td>
<td>2.8</td>
</tr>
<tr>
<td>F2</td>
<td>0.87</td>
<td>30</td>
<td>200</td>
<td>2700</td>
<td>2500</td>
<td>2085</td>
<td>2</td>
<td>2.8</td>
</tr>
<tr>
<td>F3</td>
<td>0.87</td>
<td>30</td>
<td>200</td>
<td>2700</td>
<td>2500</td>
<td>2085</td>
<td>3</td>
<td>2.8</td>
</tr>
</tbody>
</table>

The 6 panels are modelled as either one-way or two-way slabs. When they are modelled as one-way slabs, only the boundaries on the left and the right hand sides are fixed, whereas all the four sides are fixed when they are modelled as two-way slabs. Figure 2 compares the P-I diagrams of the 6 panels. As shown, increasing the slab reinforcement ratio from 1.4% to 4.0% greatly enhances its blast load resistance capacity. Similarly, applying an FRP layer is also very effective. Even a thin FRP layer of 1.0 mm makes the panel’s blast loading resistance stronger and comparable to increasing the reinforcement ratio from 0.87% to 4.0%. Since FRP layer can also serve as a catchment screen to block debris from the damaged panels, it is an ideal strengthening material for RC structural panels.

RANDOM LOADING AND STRUCTURAL PARAMETERS

A number of possibilities that would make the adopted blast loadings and structural parameters used in the design analysis not exactly the same as the respective true values. These include the errors in the predictive models, measurement errors, fluctuations with the changing environmental conditions, construction quality control and deteriorations. These variations will affect the predictions of structural responses to blast loadings. They are usually accounted for with probabilistic and reliability analysis.

Variations in Blast Load Predictions

Low and Hao (2001) considered several different blast loading prediction methods over a scaled distance range of 0.24 m/kg$^{1/3}$ to 40 m/kg$^{1/3}$, resulting in an average value for the COV of peak reflected pressure of 0.3227 and loading duration of 0.13. The results also show that the variations are substantially larger in the range of scaled distance less than 1.0 m/kg$^{1/3}$ and larger than 10 m/kg$^{1/3}$. For a scaled distance range of 1.19 m/kg$^{1/3}$ to 23.79 m/kg$^{1/3}$, the study by Bogosnian et al. (2002) found the average COV’s for pressure and impulse of 0.24 and 0.18 respectively. Netherton and Stewart (2010) conducted a comprehensive analysis to study the blast load variability and accuracy of
predictive models. It was found that the peak reflected pressure and positive loading duration predicted according to TM5-1300 reflect the median values of blast loading, and the TM5-1300 reflected impulse is 40% higher than the median value with a probability of exceedance of 4% to 23%, implying significant overestimation of the blast loadings acting on the structure.

Random variations of RC structural parameters have been studied by many researchers. A review of those random variations can be found in (Low and Hao 2001, Hao et al 2010). The study of the variations in FRP and bond strength properties is relatively less. Atadero and Karbhari (2005) examined FRP strength variation, and found COV’s ranging from 0.05 to 0.2. Wang et al. (2010) studied the COV’s of FRP strength, and found they range from 0.04 for shop-manufactured composites with high quality control to 0.24 for field-manufactured composites with average quality control. Atadero and Karbhari (2008) noted that it is difficult to define the variation of epoxy bond strength, and the bond strength also depends on other parameters such as the tensile strength of concrete. Mutalib (2011b) reviewed the available data in literature and suggested a COV of 0.1 for bond strength. In this study, the random variations of RC structural parameters given in (Hao et al. 2010) and those for FRP properties reviewed above are adopted in the analysis. They are listed in Table 2. Owing to the lack of data, all the variations are assumed having normal distributions.

Variations in Structural Parameters

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### Table 2. Statistical variations of slab parameters

<table>
<thead>
<tr>
<th>Variation</th>
<th>ρ (%)</th>
<th>$f_{cu}$</th>
<th>d</th>
<th>H</th>
<th>B</th>
<th>$t_{frp}$</th>
<th>$t_{frp}$</th>
<th>$f_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>COV</td>
<td>0.1</td>
<td>0.11</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
<td>0.07</td>
<td>0.1</td>
</tr>
<tr>
<td>Distribution</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
</tr>
</tbody>
</table>

### RELIABILITY ANALYSIS

Considering random variations of the slab parameters, the P-I curves shown in Figure 2 will vary accordingly. Similarly the predicted reflected pressure $P_r$ and impulse $I_r$ at each scaled distance will also vary. Taking these variations into consideration as shown in Figure 3, the probabilities of the RC slabs corresponding to the three damage levels can be estimated. The limit state function is

\[
g(X) = D(\rho, f_{cu}, d, H, b, f_{frp}, t_{frp}, f_e, P_r, t_d) - D^*(P_r, t_d) = 0
\]

in which $D$ is the distance from the origin of the P-I diagram to the intersection point between the P-I curve and a line connecting the origin of the P-I diagram and the loading point $(P_r, I_r)$, and $D^*$ is the distance from the origin of the P-I diagram to point $(P_r, I_r)$. More details of constructing the limit state function can be found in Hao et al (2010). The constructed limit state function is programmed and linked to CAREL as its user subroutine in calculation the probabilities at different damage levels.

### RESULTS AND DISCUSSIONS

The probabilities corresponding to the three damage levels of the above panels are calculated and shown in Figure 4. As shown, increasing the slab reinforcement ratio is an effective way to reduce the slab failure probability. FRP strengthening is very effective to protect RC slabs against blast loads. Applying a 1 mm thick layer is more effective than increasing the reinforcement ratio from 0.87% to 4.0%. However, additional benefit by further increasing the FRP layer thickness to 2 mm and 3 mm is not prominent. Without FRP strengthening, the one-way RC slab with 0.87% reinforcement might experience some low level damage when the scaled distance is about or less than 3.5 m/kg$^{1/3}$. With FRP strengthening, this scaled distance reduces to about 2.2 m/kg$^{1/3}$. Without FRP strengthening the slab will collapse when the scaled distance is less than or equal to about 1.3 m/kg$^{1/3}$ when the slab is strengthened with a FRP layer.

### CONCLUSIONS

This paper presents reliability analysis results of RC slabs without and with FRP strengthening to against blast loads. The results show that FRP strengthening is very effective in enhancing RC slab’s capacity to resist blast loads. Applying a 1 mm FRP layer is more effective than increasing the reinforcement ratio from 0.87% to 4.0%. However, the benefit of FRP strengthening is not prominent with further increasing the FRP thickness. Since FRP layer can also act as a debris catchment system, it can be a good strengthening choice of RC slabs.
REFERENCES